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14. ABSTRACT

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Evaluation of Baroclinic ADCIRC Using a Process-Oriented Test Along a Slope

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EVALUATION OF BAROCLINIC ADCIRC USING A PROCESS-ORIENTED TEST ALONG A SLOPE

K.M. Dresback[1], E.M. Tromble[1], D.G. Reid[1], R.L. Kolar[1], T.C.G. Kibbey[1], C.A. Blain[2], R.A. Luettich, Jr.[3], C.M. Szpilka[1]

ABSTRACT

Process-oriented tests, such as those suggested by Haidvogel and Beckmann (1999), are often utilized in the validation of baroclinic processes in shallow water models. In a previous analysis, the so-called “lock-exchange” or “dam break” problem on a flat slope, wherein a vertical barrier that separates water of different densities is removed at time zero, was utilized in the validation of the baroclinic additions to the shallow water ADCIRC (ADvanced CIRCulation) model. More specifically, a laboratory-scale model was utilized to capture high-resolution data sets of the lock-exchange problem. These data sets allowed for direct comparison throughout the domain of the experimental and numerical results. Results showed good agreement between model and laboratory results, sans the shear instabilities along the interface. Using these same techniques, we analyzed a density front along a slope, the “gravity adjustment” test case suggested by Haidvogel and Beckmann (1999). In this analysis, water of different densities is separated by a vertical barrier that is removed at time zero, allowing the water with the heavier density to travel down the slope. Data is captured every 0.2 seconds using high-resolution digital photography, with salt concentration extracted by comparing pixel intensity of the dyed fluid against calibration standards. Herein, experimental results are compared to numerical results for the location and thickness of the front, along with the average root mean square errors of the salinity field.

INTRODUCTION

In order to continue validation of baroclinic enhancements to the shallow water ADCIRC model (Luettich and Westerink, 2004; Dresback and Kolar, 2004; Dresback et al., 2011), laboratory methods were applied to obtain a data set for the gravity adjustment test case suggested by Haidvogel and Beckmann (1999). First, the experimental

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methods and results are presented. Subsequently, the model background and results are reported, and comparisons are made between the laboratory and model results. Finally, a summary and outline for future work conclude the document.

EXPERIMENTAL METHODS

The gravity adjustment experiments documented herein were conducted using the same custom density cell that was employed previously by Kolar et al. (2009) for the lock-exchange experiment. A general overview of the density cell and experimental methods will be presented for completeness, but the reader is referred to the aforementioned journal article for additional details.

CELL

The custom designed and constructed density cell has internal dimensions of 58.4 cm (w) x 29.5 cm (h) x 2.54 cm (d). The cell is constructed from translucent white high-density polyethylene for the back, sides, and bottom; the front of the tank is high-quality transparent cast acrylic. The tank has a vertical baffle in the center that allows fluids of two different densities to be separated for the set-up of the lock-exchange experiment. The gravity adjustment problem examined herein requires an asymmetrical division of water densities, so the middle baffle was not employed. Rather than install a second spring-loaded baffle at the desired location approximately 8.6 cm from the left side of the tank, the division of fluids was achieved using a manually-removed vertical divider. For this study, a 17.2 ppt salt solution was created for the high-density water, while fresh water (0.0 ppt salt concentration) occupied the majority of the cell at initial conditions. The salt water solution, with green dye as an indicator, was prepared in 2-liter batches using 17.5 grams of table salt per 1017.5 grams of solution. Previously, this cell was utilized for flat-bottom simulations. The gravity-adjustment problem requires a non-constant bathymetry set-up. A picture of the density cell with the sloped, foam insert is shown in Figure 1. The foam insert consists of two pieces, with each piece occupying one side of the tank on either side of the baffle in the middle.

Figure 1 Density cell with sloped insert.

IMAGING

The images were captured using the combination of a Hitachi KP-M2 monochrome analog video camera with a 1/2” charge-coupled device and an EPIX SV5 capture board set to a constant rate of 5 frames/s. Selected images captured during the one experimental run are shown in Figure 2. A dark red 52 mm filter is used to improve detection of the green dye, which is used to delineate salinity concentration of the water

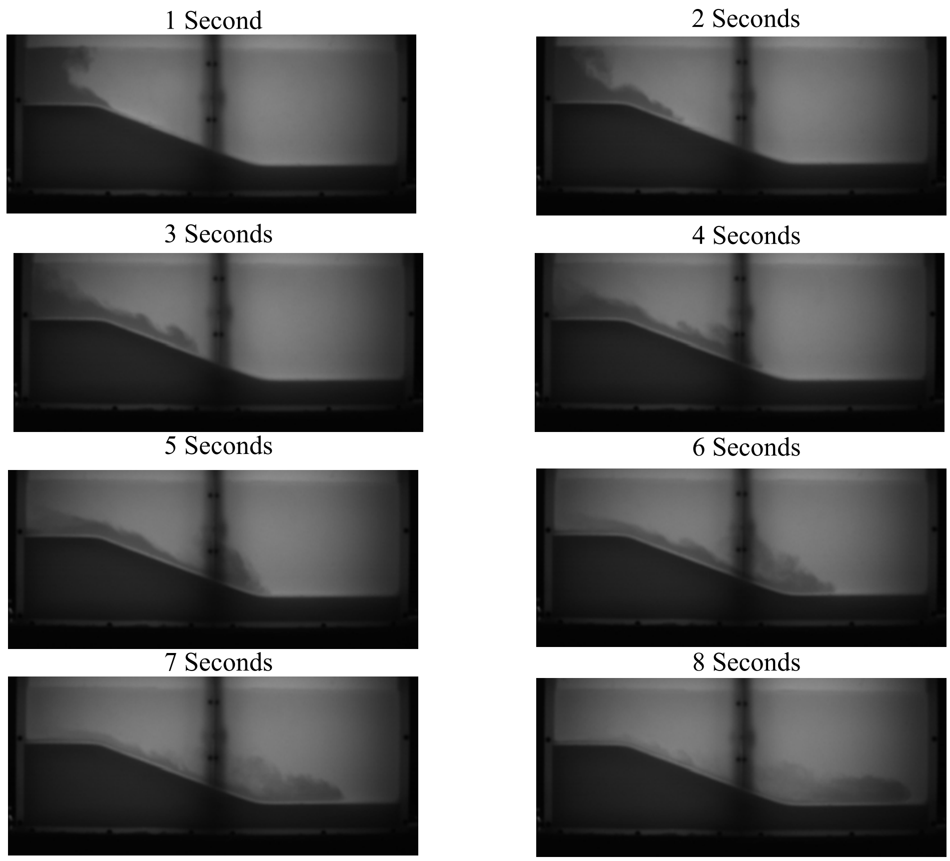

Figure 2 Time evolution of images of laboratory experiment for the gravity adjustment problem.

throughout the density cell. The images were captured at a resolution of 640 x 480 pixels, then downsampled using average downsampling. The concentration at each pixel is calculated using (1), where the standard and sample light absorbance are calculated from the standard, blank, dark, and sample images using (2) (Workman and Springsteen, 1998) and (3), respectively,

$$c^i_{samp} = c^i_{std}\frac{A^i_{samp}}{A^i_{std}} \tag{1}$$

$$A^i_{std} = -\log\left(\frac{I^i_{std} - I^i_{dark}}{I^i_{blank} - I^i_{dark}}\right) \tag{2}$$

$$A^i_{samp} = -\log\left(\frac{I^i_{samp} - I^i_{dark}}{I^i_{blank} - I^i_{dark}}\right) \tag{3}$$

where c^i_{std} is the initial saline concentration for a given experiment; c^i_{samp} is the concentration at a given pixel in a sample image (non-standard image, e.g., during an experimental run); A^i_{samp} is the light absorbance of a given pixel in a sample image; A^i_{std} is the light absorbance of the standard; I^i_{samp}, I^i_{std}, I^i_{blank}, and I^i_{dark} are the intensities of pixel i for the sample, standard, blank, and dark images, respectively.

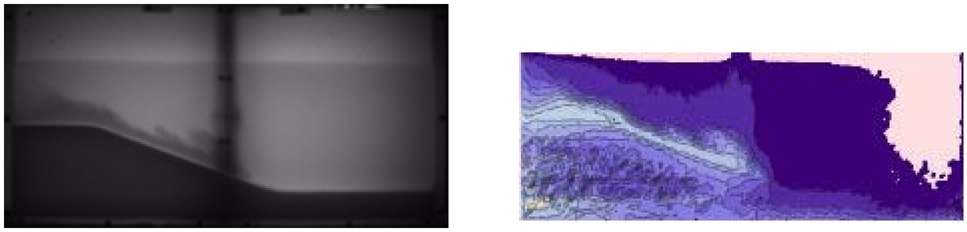

Figure 3 Laboratory results 4.0 seconds into the gravity adjustment experiment. The left panel shows the image captured, while the right panel is the digitized image of the captured image in the left panel. The colors in the right panel correspond to different salinity values; the beige and dark purple correspond to low salinity values, while the lightest purple colors represent high salinity values. Noise in the lower left is related to imaging of the foam insert.

The standard image is of the cell containing the dyed solution in the entire cell, while the blank image is of the cell containing undyed, fresh water in the entire cell; the dark image is captured with the lens cap on to obtain a measure of the background signal produced by the camera. An example of the digitized data, depicting the salinity concentration at each point, is shown in the right panel of Figure 3.

The downsampling was performed following the computation of the concentration at each pixel, as shown schematically in Figure 4. Average downsampling was used to reduce the resolution of the data from the captured resolution to the resolution desired for analysis; the downsampled resolution for the area of interest, i.e., the density cell, was 100 x 38. Average downsampling means the salinity concentration value at each pixel is the arithmetic mean of the pixels it replaces.

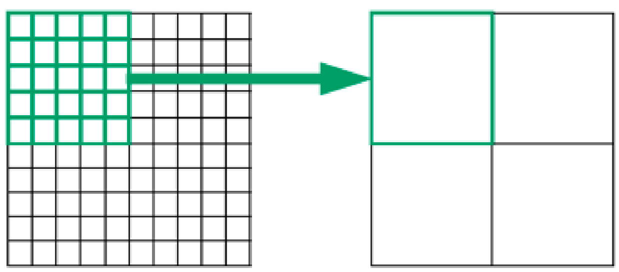

Figure 4 Schematic of raw image downsampling.

EXPERIMENTAL RESULTS

Figure 5 presents several snapshots of the laboratory results. Initially, the dense fluid is confined to the upper left corner of the tank, constrained by the insert and baffle; the salt wedge is the gray area. Underneath the salt wedge, the insert is visible, to some extent. Throughout the images, the left side of the insert shows up as a variety of colors, mostly in the light purple range. However, the right side of the insert is not as easy to see, and the reader is referred to Figure 2 for clarification, because the insert is more clearly visible in the original laboratory images. The second image shows the salt water starting down the slope of the insert, while the majority of the high-density water remains close to the left-most wall of the tank. After four seconds, the high-density wave has reached the center of the tank, and fresh water has replaced the salt water along the top of the tank. The salt water plume continues moving to the right along the top of the insert, and after eight seconds, the front edge of the salt water is approaching the wall on the right side of the density cell.

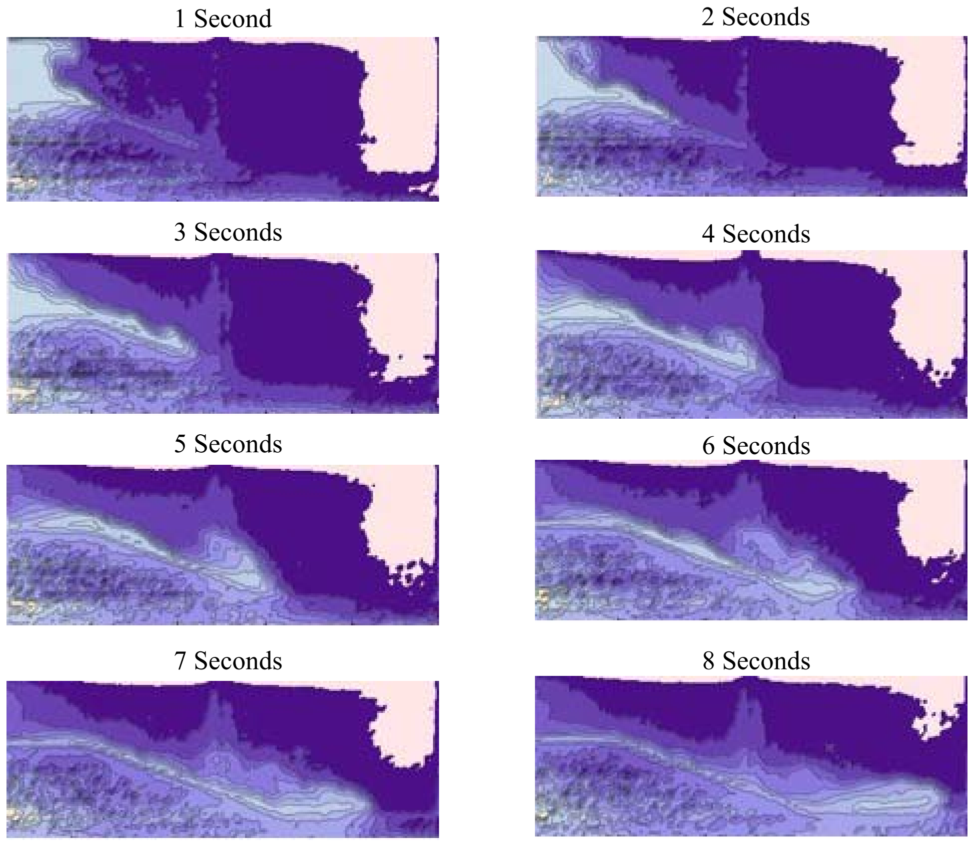

Figure 5 Time evolution of processed laboratory data for the gravity adjustment problem. The colors correspond to different salinity values; the beige and dark purple correspond to low salinity values, while the lightest purple colors represent high salinity values. The foam insert and the housing for the baffle in the center of the tank are visible in the digitized data.

Model Background

The motivation for the work presented herein is the continued effort to validate prognostic baroclinic modifications to the ADCIRC hydrodynamic code, which is based on the Generalized Wave Continuity (GWC) reformulation of the shallow water equations (Kinnmark, 1986; Luettich and Westerink, 2004; Lynch and Gray, 1979). Specifically, ADCIRC solves the GWC equation, (4), for water surface elevations, and the non-conservative form of the momentum equation is solved to obtain the velocities.

$$W^G = \frac{\partial L}{\partial t} + GL - \nabla \cdot \mathbf{M}^c \qquad \textbf{(4)}$$

where L and $\mathbf{M}^c$ represent the primitive continuity and conservative momentum equations, respectively, while G is the numerical penalty parameter.

As reported by Kolar et al. (2009), the transport equation for temperature and salinity was added to ADCIRC in non-conservative form:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} - \frac{\partial}{\partial x}\left(N_H\frac{\partial c}{\partial x}\right) - \frac{\partial}{\partial y}\left(N_H\frac{\partial c}{\partial y}\right) - \frac{\partial}{\partial z}\left(N_V\frac{\partial c}{\partial z}\right) = 0 \quad \textbf{(5)}$$

where c represents the species being transported, (u, v, w) are the velocities in the (x, y, z) directions, and N_H and N_V are the horizontal and vertical diffusion coefficients, respectively.

MODEL RESULTS

The initial ADCIRC model simulation for the gravity adjustment problem was performed with the parameter values used by Kolar et al. (2009). Adjustments were made to the parameter values based on qualitative observations on the original results. The ADCIRC model results reported herein were generated using the following parameters: horizontal diffusion = 0.002 $\mathrm{m^2/s}$; horizontal eddy viscosity = 0.001 $\mathrm{m^2/s}$; G = 0.0001 $\mathrm{s^{-1}}$; and a resolution of 100 nodes in the x-direction and 38 nodes in the sigma direction. Thus, while the G value was kept the same, the horizontal diffusion was increased by an order of magnitude (from 0.0002 $\mathrm{m^2/s}$) and the horizontal eddy viscosity was decreased by a factor of 3.3 (from 0.0033 $\mathrm{m^2/s}$).

The mass balance results for the ADCIRC simulation are shown in Figure 6. The mass balance is represented by the average salt concentration throughout the domain. In theory, both the volume and mass in the system should not change in time. Therefore, the average concentration should also be constant throughout the simulation. The average salt concentration was calculated for each every 0.2 seconds, which corresponds to the time step for the image capture for the laboratory results.

During the initial gravity adjustment, while the dense water is moving from the starting position towards the wall on the right side, there is an increase in mass in the ADCIRC model, as indicated by the rise in the average salinity concentration. However, the mass balance is fairly good for the portion of the simulation after the initial gravity adjustment, as depicted by the approximately horizontal line over the last twenty seconds in the graph. The mass imbalance may be related to start-up noise as the solution changes from a rectangular salt wedge to a plume that is moving down the slope.

COMPARISON OF MODEL AND LAB RESULTS

The laboratory experiment was performed in triplicate. However, one of the sets of data (the computed salinity values), was not consistent with the data from the other two runs. The computed salinity values for the third data set were approximately half as large as the values for the other two data sets. Therefore, the aberrant data set was not used, and the lab values from the other two runs were used for comparisons to the model.

Two metrics were employed for comparison of the model and experimental results. The first is a comparison of the salinity results throughout the entire domain. In previous experiments (Kolar et al., 2009), the model node positions were coincident

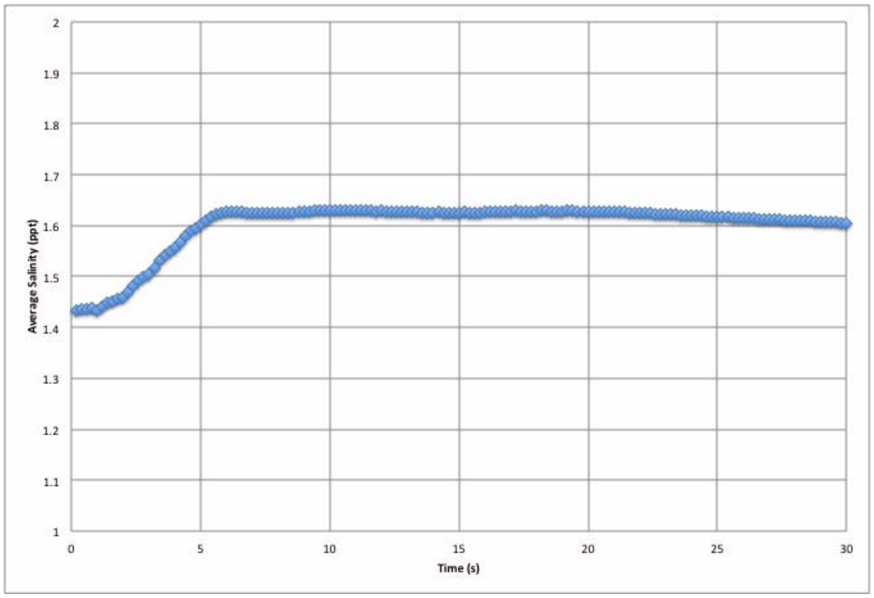

Figure 6 Average salinity (ppt) throughout the ADCIRC simulation for the gravity adjustment problem.

with the locations for the laboratory results. In other words, the flat bathymetry led to a structured grid for both ADCIRC and the digital imaging. However, because the bathymetry changes with spatial location for the gravity adjustment problem, the ADCIRC model node positions are not coincident with the laboratory results, which uses a rectangular array of pixels; the laboratory results contain information in the portion of the density cell that is occupied by the foam insert, whereas the bottom of the ADCIRC model resides at the level of the top of the foam insert.

Two options were considered for computing the RMS error, given by (6), which requires coincident node locations: 1) interpolate laboratory values onto ADCIRC node locations and 2) interpolate ADCIRC values onto laboratory point locations that fall within the ADCIRC domain, i.e., locations that are at or above the top of the insert. Each of the two options preserves geometric balance in one fashion. By interpolating the laboratory values onto the ADCIRC node locations, the first method maintains an equal number of points in each column in the domain. Therefore, each column contributes the same amount of weight to the total RMS computation. In contrast, the second method gives equal weight to each volume of fluid within the domain. For the results herein, the second method was used, and the ADCIRC output was mapped to the laboratory output grid. The laboratory salinity values used to compute the RMS error were the average (arithmetic mean computed at each time and space location) of the two compatible laboratory data sets.

$$\mathrm{RMS}^t = \sqrt{\frac{1}{n}\sum_i (c_{lab}^{i,t} - c_{model}^{i,t})^2} \qquad \mathbf{(6)}$$

The time-evolution of the salinity RMS error values between the ADCIRC and laboratory results are shown in Figure 7. As is readily apparent, there is some error that is a result of the laboratory set-up and image-capture processes. This inherent error is suggested by the non-zero RMS error at the initial time (0.2 s into the simulation and experiment), when the solution is very similar to the initial conditions, which would have zero error in an ideal set-up. However, the average salinity RMS error of 2.36 ppt throughout the simulation is less than the results for previous model and laboratory comparisons presented by Kolar et al. (2009), which were 3.43 ppt (symmetric) and 3.74 ppt (asymmetric).

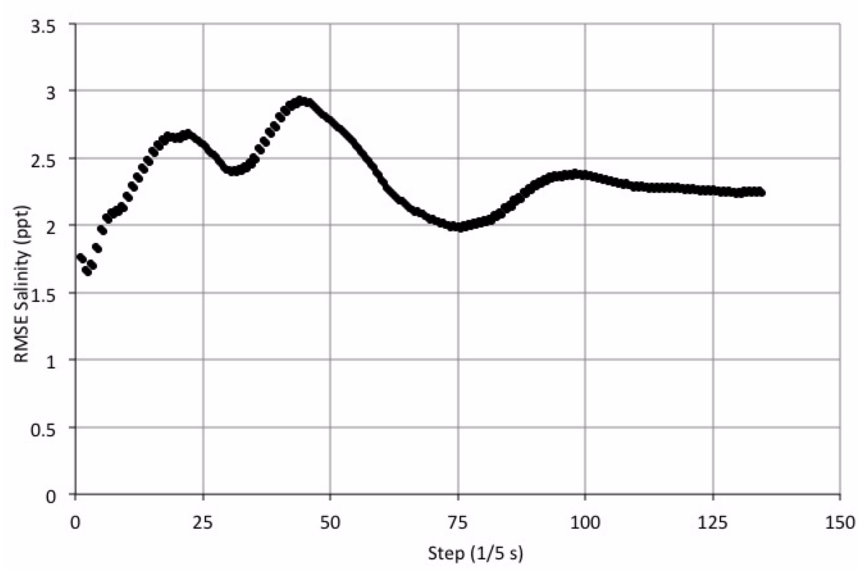

Figure 7 RMS error in salinity (ppt) between the ADCIRC and laboratory results at each time step (every 1/5 s) during the first 30 seconds of the gravity adjustment problem.

As seen in Figure 7, the salinity RMS error increases from a minimum at the initial times as the mass of dense water moves down the slope. There is a slight decrease in RMS error prior to the dense water reaching the right side of the domain. The maximum RMS errors correspond to the time immediately following the arrival of the salt water at the right wall in the density cell. Eventually, the RMS error values level off at about 2.25 ppt as the simulation reaches equilibrium conditions. The error is asymptotic, which is expected based on the test problem; neither the laboratory nor the model results should have a poorly behaved concentration field. The asymptotic error suggests consistency in the procedure to compute salinity values from the imaged data, as well. Finally, the asymptotic error is a measure of the validity of the procedure, and efforts to minimize the error inherent to the laboratory, imaging, and data processing steps are an area of future research.

The second metric to compare the model and laboratory results is the propagation speed of the dense water as it moves down the slope. The movement of the position of the 50% contour line (50% of the initial concentration of the salt water in the experiment) is used as a surrogate for the movement of the mass of dense water. For this analysis, the location of the 50% line along the bottom of the computational ADCIRC domain (i.e., along the top of the insert for the laboratory experiments) was calculated and reported. The first component for determining the 50% contour line is determining the nodes along the computational bottom boundary. Then, the conceptual algorithm used at each time step is as follows, and is consistent for both model and laboratory data: 1) starting at the left side (which assumes the high-density water is moving from left to right), the first instance of a value greater than 50% of the initial maximum is located, which means that we have moved through the low-salinity area (if it exists) and moved into an area of dense water, 2) the first instance of a salinity less than 50% of the initial maximum, to the right of the location found in Step 1, is found, which signifies we are on the low-salinity side of the front 50% contour, and 3) the location of the 50% contour is computed from the node locations and salinity values using a linear interpolation. A comparison of the temporal evolution of the position of the 50% contour line, for both the laboratory and model results, is shown in Figure 8. In this case, the individual laboratory runs were used, rather than the averaged data. The laboratory data is not as linear as the model data, which may be a result of there not being a distinct 50% contour line in the laboratory data, whereas the transition in density between the salt plume and the fresh water is more linear in the model.

The initial positions of the 50% contour lines coincide, as expected. However, the propagation speed is greater for the laboratory results than for the model, which is indicated by the position of the 50% contour in the laboratory results being greater, for the same time, than the position of the 50% contour line in the ADCIRC model. The majority of the error in the propagation speed occurs within the first 2 seconds, which suggests the ADCIRC model is missing an important component of the physics that occurs during the initial stages of the gravity adjustment problem. Specifically, there is error in the transition from a vertical salt wedge to a plume moving down the slope. However, overall, the model does a good job representing the propagation of the dense water down the slope.

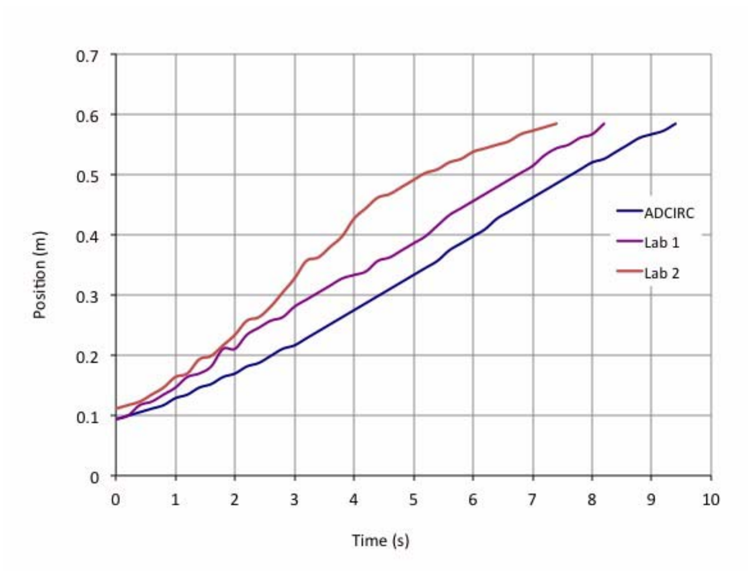

Figure 8 Comparison of the temporal evolutions of the positions of the 50% contour line in the model and laboratory results prior to the mass of dense water arriving at the wall on the right side of the density cell.

The average speed of the 50% line in the ADCIRC model data, from the start until the time when the salt wedge arrives at the right side of the domain, is 0.052 m/s. For the period of time after the first two seconds, the average speed of propagation is 0.056 m/s. The location of the 50% contour line in the laboratory runs diverges after about 2 seconds, with the salt plume in the experiment labeled “Lab 2” traveling more rapidly than the salt plume in the other run. The overall average speed for “Lab 2” is 0.064 m/s, while the average speed after the first two seconds is 0.065 m/s. For “Lab 1,” the average speed before it reaches the right wall, as well as the average speed after the first two seconds, is 0.060 m/s. In comparison to the laboratory data, the general movement of the salt plume down the slope is modeled reasonably well by ADCIRC.

SUMMARY

Herein, we have presented a non-constant bathymetry baroclinic mixing problem. The data collection methods presented by Kolar et al. (2009) were repeated for this gravity adjustment test case. Additionally, the ADCIRC hydrodynamic model was used to compute model results for the test case, and the results from the model and laboratory data sets were compared.

The average RMS error for salinity was 2.36 ppt, which is about 1/3 less than the average salinity error between the model and laboratory results for the test cases presented by Kolar et al. (2009). For the model parameter set used herein, the salt water propagates down the slope too slow in comparison to the data from the laboratory results; the 50% contour line arrives at the right wall of the density cell 7.4 and 8.2 s into the two laboratory tests, whereas the 50% contour line reaches the right side of the ADCIRC domain 9.4 s into the model simulation. Adjustments may be necessary to model parameters to improve the match in propagation speed between the model and laboratory results.

FUTURE WORK

The main immediate focus of future work in this gravity adjustment test case endeavor is improving the laboratory data set. Specifically, a new, larger density cell devoted to this test case will be a main focus. Emphasis will be placed on making the entire cell water tight, as well as limiting the amount of water exchange between the main area of the tank and the bottom insert. Additionally, a removable baffle will be positioned at the edge of the plateau on the left side of the tank. Furthermore, increasing the size of the tank will allow for a greater duration for the test case, as the current duration of the initial salt plume propagation down the slope is relatively short, and synchronization between removal of the baffle and camera timing would decrease error (currently up to 0.2 seconds) related to capture of images at the start of the experiment.

The second emphasis in future work is related to model analysis. ADCIRC simulations will be performed to analyze the ability of the model to reproduce the new experimental results. Additionally, sensitivity of ADCIRC results to changes in model parameters also needs to be systematically examined.

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